Summary of Research

NASA-Ames Cooperative Agreement Number NCC 2-662

MODELLING ATMOSPHERIC SCATTERERS USING SPACECRAFT OBSERVATIONS

From April 1, 1990 through April 30,1999

Submitted to
Dr. Christopher P. McKay, Technical Officer
National Aeronautics and Space Administration
Ames Research Center, MS 245-3
Moffett Field, California 94035-1000

Prepared by
Dr. Kathy A. Rages, Principal Investigator
Space Physics Research Institute
572 Hyannis Drive
Sunnyvale, California 94087-1315
(408) 736-9705

SEP 14 1999
2021-3
CASI

Modelling Atmospheric Scatterers Using Spacecraft Observations

The period covered by this cooperative agreement included the analysis of data from the Voyager encounter with Neptune and Triton and the primary Galileo mission to Jupiter (including the Galileo Probe entry into Jupiter's atmosphere), as well as continued work on Uranus' seasonal variability using the Voyager encounter data as a baseline.

Analysis of Voyager Triton Limb Images ...

High resolution images of planetary limbs can be used to derive information about the vertical structure and single scattering properties of scatterers in the upper atmosphere (assuming, of course, that the planet has an atmosphere). Because of the very long slant path through the atmosphere of lines of sight grazing the edge of the planet, such observations generally reveal information about altitudes corresponding to optical depths in the range 10^{-5} to ~0.03. In this respect limb studies complement observations of the disk of the planet, which are most sensitive to structure and composition at optical depths of 0.1 to ~3. Also, extinction as a function of altitude can be derived in a more-or-less direct fashion from a limb intensity scan. If there are any discrete scattering layers present they can be observed directly instead of being inferred from (probably ambiguous) fits of atmospheric scattering models to observations of specific intensity (I/F) from the planet as a whole (Pollack *et al.* 1987; Rages and Pollack 1983).

Voyager images of Triton's limb reveal the presence of scattering clouds and hazes above the surface, with considerable latitudinal variability (Pollack *et al.* 1990). Standard algorithms for calculating scattered specific intensities (I/F's) near the limb of a spherical atmosphere were combined with Mie theory to derive models for the single scattering properties and the vertical distribution of these clouds and hazes. Near 14°S latitude, 275°W longitude only haze was present, with optical depth ~0.01 in violet and ~0.004 in orange. Near 52°S latitude, 124°W longitude condensation clouds were also present below 6 km, with optical depth $\gtrsim 0.1$ and mean particle radii either near 0.25 μm or near 0.7 μm (Rages and Pollack 1992).

... and Neptune Limb Images ...

Voyager 2 obtained a high-phase-angle clear-filter image of Neptune's limb at ~30°S latitude with 2 km spatial resolution. Inversion of the radial intensity profile across the limb reveals a rapid increase in extinction with decreasing altitude near the 12-mbar pressure level, about where photochemically produced ethane would be expected to condense. At about 30 mbar, the haze particle radius and number density are found to be 0.13 ± 0.02 μm and 5 ± 3 cm^{-3}, respectively. The total haze extinction optical depth is ~0.003 above 15 mbar, and is mostly due to scattering rather than absorption, which makes heating due to absorption of sunlight by the haze inadequate to account for Neptune's observed stratospheric temperature inversion (Baines *et al.* 1993; Moses *et al.* 1995).

The most prominent albedo feature on Neptune at the time of the Voyager encounter was the Great Dark Spot and accompanying Bright Companion at ~27°S. There has been speculation that the cores of features such as the Bright Companion might be convective columns with tops punching through the "cold trap" of the tropopause at ~150 mbar, and as such might serve as sources for the observed excess of methane gas in the stratosphere. A comparison of the center-to-limb brightness curves of the Bright Companion in the Voyager wide-angle filters with those of its unperturbed surroundings revealed that, despite its high contrast in the methane absorption band at 619 nm, the top of the Bright Companion may lie as deep as the 400 mbar pressure level. This is well below the tropopause, and would eliminate the Bright Companion and similar features as sources for the observed excess methane mixing ratio in the stratosphere (Rages *et al.* 1996).

... and Galileo Images of Venus' Limb ...

The Galileo spacecraft flew past Venus on its roundabout trajectory to Jupiter in February 1990. Imaging data included six images of the limb between ~10°N and ~60°N (three pairs consisting of one violet image and one 1-μm image each). These images were inverted to yield vertical extinction profiles using the previously developed procedure. A region of enhanced extinction was clearly visible in both filters at the highest latitude and an altitude of 91 km (pressure ≈0.3 mbar). At 48°N a similar feature was visible in the 1 μm filter at an altitude of 88 km (≈0.6 mbar) and there was also some enhancement in the violet extinction at this altitude, although it was far less conspicuous. Near the equator there was a change in the mean scale height near 87 km (1 bar), but no sign of any other feature. The fact that the extinction at a given altitude is much the same at 0.41 μm (violet) and 1 μm indicates that the dominant sources of scattered light at all three latitudes are probably greater than 0.1-0.2 μm in size. Particles smaller than this would be Rayleigh scattering, and the extinction coefficient for Rayleigh scatterers would be expected to drop by more than an order of magnitude between 0.41 μm and 1 μm. A comparison of the extinction profiles at 57°N and 48°N gives the impression that the layer of enhanced extinction may drop to lower altitudes at lower latitudes. (Belton *et al.* 1991).

... and (finally) Jupiter's Limb

In December 1996, during orbit E4, Galileo used its Solid State Imaging subsystem (SSI) to take four images of Jupiter's equatorial limb and four images of the limb in the transition zone between north temperate latitudes and the northern polar region. Galileo made images of each region in violet (mean wavelength 411 nm) and near infrared (756 nm) filters at two high solar phase angles. The images were taken close enough to Jupiter to give spatial resolutions of ~15 km/pixel, comparable to a scale height near the tropopause. They reveal the presence of stratospheric hazes in the equatorial region (9°N) and the north polar transition zone (60°N). A discrete layer detached from the limb is present at 60°N, 315°W, but not 20°further east at 60°N, 285°W. Bright streaks running roughly north-south are also present on Jupiter's crescent at 60°N. No such discrete features are seen at 9°N, where the haze appears to be more uniformly distributed in height and longitude.

Radial specific intensity (I/F) profiles across the limb were inverted to give vertical extinction profiles over ~200 km in Jupiter's stratosphere at both 9°N and 60°N. The maximum I/F in each image was used to estimate the single scattering phase function for the corresponding scattering angle, wavelength, and altitude. These phase functions required different particle sizes in the violet and near-IR filters, which probed two different altitudes. Haze distribution models were found for both latitudes in which the near-IR images constrain the haze properties near or above the 100 mbar pressure level, where the mean particle radius is about 0.45 μm and the haze number density is near 0.15 cm^{-3}. In these models the violet images constrain the haze properties near or above the 20 mbar pressure level, where the haze particle size is about 0.32 μm at 9°N and about 0.27 μm at 60°N. At this altitude, the haze number density increases by almost an order of magnitude between the equator and the polar transition region. To fit Hubble Space Telescope (HST) observations in the ultraviolet and the methane absorption band at 890 nm, these models must be modified by the addition of another scattering component, consisting of $\lesssim 0.02$ μm particles which are conservatively scattering in the near-IR and have single scattering albedos near 0.5 in the UV. This 0.02-μm haze accounts for more than 90% of the Rayleigh scattering (originally ascribed to scattering by the hydrogen-helium gas) in both filters, with a corresponding drop of a factor of ~10 in the pressure levels probed (Rages *et al.* 1999).

Latitude Bands and Temporal Variability on Uranus

Uranus undergoes extreme seasonal variations as a result of its 98° axial tilt. Since the Voyager encounter in January 1986, the subsolar latitude has shifted from its southern solstice position of 82°S to about 30°S. During the past 20 years, Uranus' brightness has varied by about 4% in blue

light (wavelength 0.472±0.021 μm) and about 11% in yellow (0.551±0.023 μm) (Lockwood *et al.* 1985; Lockwood, private communication). These changes appear to be seasonal rather than being related to solar variability, which would show up as an ~11 year periodicity. Some part of this seasonal variability may be due simply to the changing aspect of the planet as seen from Earth, since Voyager found that southern polar latitudes were somewhat brighter than regions nearer the equator.

Radiative transfer models were derived for five southern latitudes in addition to the two (22.5°S and 65°S) previously studied using Voyager images (Rages *et al.* 1991). Both τ, the optical depth of Uranus' methane cloud layer, and f_H, the product of the mean methane cloud particle size and the fraction of stratospheric haze material mixed into the methane cloud, vary by factors of ~2 between the latitudes of 10°S and 85°S. The variability observed by Lockwood exceeds that which would be caused by these latitudinal variations in atmospheric structure, by about a factor of two in the blue and about a factor of five in the yellow. Therefore Uranus is undergoing actual temporal changes in its scattering properties. Calculations show that even the most favorable combination of changes in the methane cloud optical depth and the concentration of stratospheric haze and its residue below the methane cloud produce only about 2/3 of the observed brightness changes in both filters. Some other factor, such as hemispheric asymmetry in the atmospheric structure, must be introduced to account for Uranus' observed long-term albedo changes (Rages and Pollack 1994).

Galileo Probe Nephelometer

The Galileo Probe entered Jupiter's atmosphere on December 7, 1995 and returned data for 57 minutes, down to a pressure level of about 20 bars. One of the instruments carried on the probe was a nephelometer intended to measure the scattering properties of the regions the Probe passed through. The Probe entered Jupiter's atmosphere near the edge of a 5-μm hot spot, a region where the atmosphere is much clearer than on most of the planet. The nephelometer definitely saw one thin cloud at about 1.3 bars, and very preliminary analysis indicates that this cloud is composed of particles with mean radii of 1-5 μm. The data can be fit either by spherical scatterers having radii of 0.8 μm, a real refractive index n_r of 1.7-1.8, and an imaginary refractive index n_i~0.05, or by scatterers with radii around 8 μm, a very low value of n_r ($\leq$ 1.2), and n_i=0. The high-n_r solution is consistent with the little that is known of the optical constants of ammonium hydrosulfide, the most likely constituent of a cloud at 1.3 bars, but would require the presence of some additional component to account for the absorption. The low-n_r solution requires either a very unusual composition or "fluffy" particles with many internal voids, since none of the likely bulk constituents have refractive indices below about 1.3. The cloud optical depth is near 2, over a vertical distance of ~20 km (Ragent *et al.* 1996; Ragent *et al.* 1998).

Bibliography

BAINES, K.H., H.B. HAMMEL, K.A. RAGES, P.N. ROMANI, AND R.E. SAMUELSON 1993. Clouds and hazes in the atmosphere of Neptune. In *Neptune and Triton* (D.P. Cruikshank, Ed.) University of Arizona Press.

BELTON, M.J., P.J. GIERASCH, M.D. SMITH, P. HELFENSTEIN, P.J. SCHINDER, J.B. POLLACK, K.A. RAGES, A.P. INGERSOLL, K.P. KLAASEN, J. VEVERKA, C.D. ANGER, M.H. CARR, C. R.CHAPMAN, M.E. DAVIES, F.P. FANALE, R. GREELEY, R. GREENBERG, J.W. HEAD, III, D. MORRISON, G. NEUKUM, AND C.B. PILCHER 1991. Images from Galileo of the Venus cloud deck. *Science* **253,** 1531-1536.

MOSES, J.I., K. RAGES, AND J.B. POLLACK 1995. An analysis of Neptune's stratospheric haze using high-phase-angle Voyager images. *Icarus* **113,** 232-266.

RAGENT, B., D.S. COLBURN, P. AVRIN, AND K.A. RAGES 1996. Results of the Galileo Probe Nephelometer Experiment. *Science* **272,** 854-856.

RAGENT, B., D.S. COLBURN, K.A. RAGES, T.C.D. KNIGHT, P. AVRIN, G.S. ORTON, P.A. YANAMANDRA-FISHER, AND G.W. GRAMS 1998. The clouds of Jupiter: Results of the Galileo Jupiter Mission Probe Nephelometer Experiment. *J. Geophys. Res.* **103,** 22,891-22,909.

RAGES, K., AND J.B. POLLACK 1992. Voyager imaging of Triton's clouds and hazes. *Icarus* **99,** 289-301.

RAGES, K.A., AND J.B. POLLACK 1994. Modeling Uranus' Temporal Variability. *Bull. Amer. Astron. Soc.* **26,** 1093.

RAGES, K. 1995. WFPC2 photometry of features near the Galileo probe entry latitude. *Bull. Amer. Astron. Soc.* **27,** 1134.

RAGES, K.A., H.B. HAMMEL, AND C.P. MCKAY 1996. Vertical structure of the 1989 Great Dark Spot and Bright Companion. *Bull. Amer. Astron. Soc.* **28,** 1077.

RAGES, K., H.B. HAMMEL, AND G.W. LOCKWOOD 1998. Changes in Uranus' atmosphere since the Voyager encounter. *Bull. Amer. Astron. Soc.* **30,** 1097.

RAGES, K., R. BEEBE, AND D. SENSKE 1999. Jovian stratospheric hazes: The high phase angle view from Galileo. *Icarus* **139,** 211-226.

Other References

LOCKWOOD, G.W., B.L. LUTZ, D.T. THOMPSON, AND E.S. BUS 1985. The albedo of Uranus in 1985. *Bull. Amer. Astron. Soc.* **17,** 744.

POLLACK, J.B., K. RAGES, S.K. POPE, M.G. TOMASKO, P.N. ROMANI, AND S.K. ATREYA 1987. Nature of the stratospheric haze on Uranus: Evidence for condensed hydrocarbons. *J. Geophys. Res.* **92,** 15,037-15,065.

POLLACK, J.B., J.M. SCHWARTZ, AND K. RAGES 1990. Scatterers in Triton's atmosphere: Implications for the seasonal volatile cycle. *Science* **250,** 440-443.

RAGES, K., AND J.B. POLLACK 1983. Vertical distribution of scattering hazes in Titan's upper atmosphere. *Icarus* **55,** 50-62.

RAGES, K., J.B. POLLACK, M.G. TOMASKO, AND L.R. DOOSE 1991. Properties of scatterers in the troposphere and lower stratosphere of Uranus based on Voyager imaging data. *Icarus* **89,** 359-376.